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(54) **INTELLIGENT COOLING FOR DIRECTED ENERGY SYSTEMS**

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See application file for complete search history.

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**F25B 15/06** (2006.01)

(57) **ABSTRACT**

Disclosed are systems and methods of intelligently cooling thermal loads by providing a burst mode cooling system for rapid cooling, and an auxiliary cooling system that controls the temperature of the thermal load and surrounding environment between burst mode cooling cycles. The system may be used to provide pulses of cooling to directed energy systems, such as lasers and other systems that generate bursts of heat in operation.

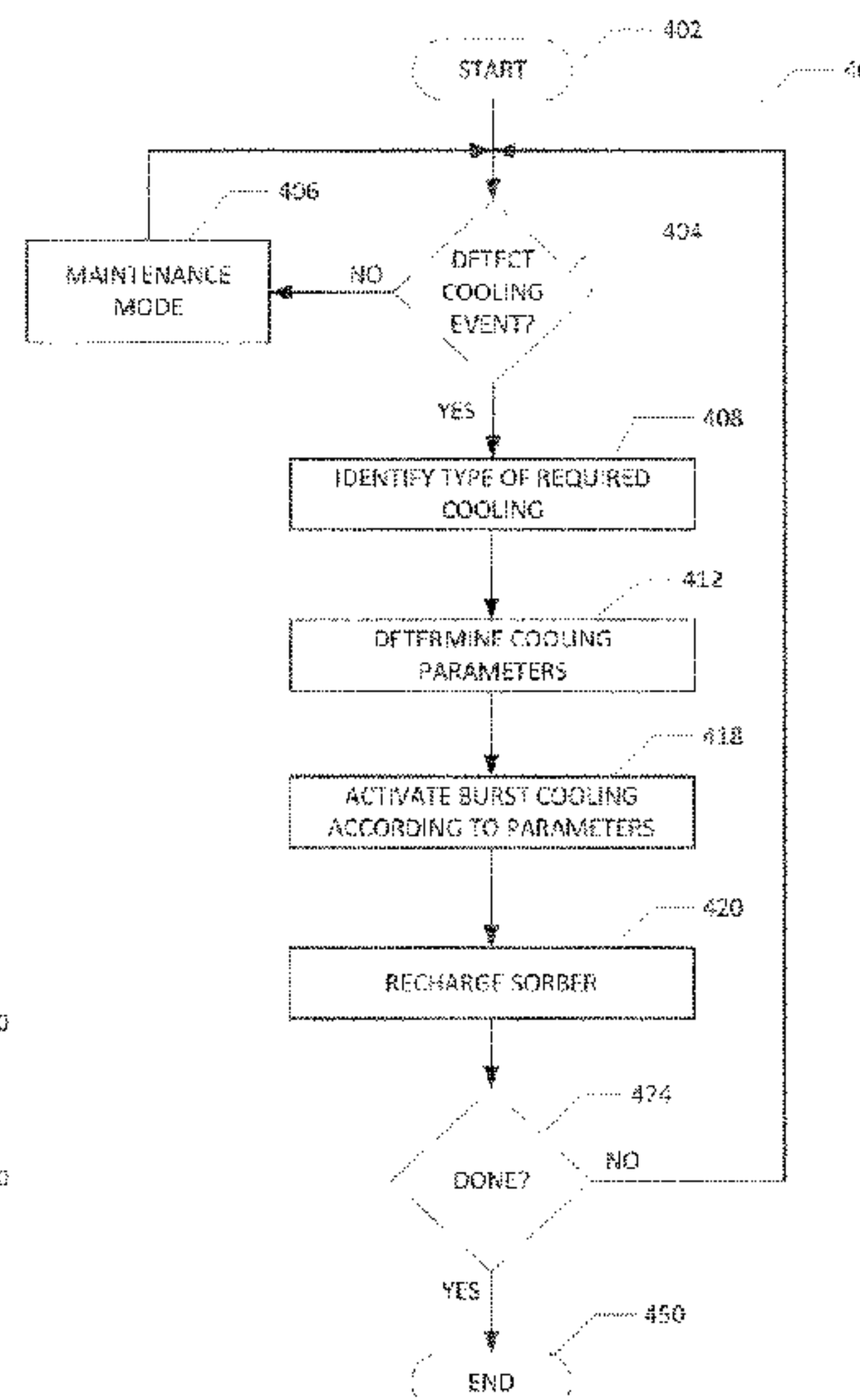
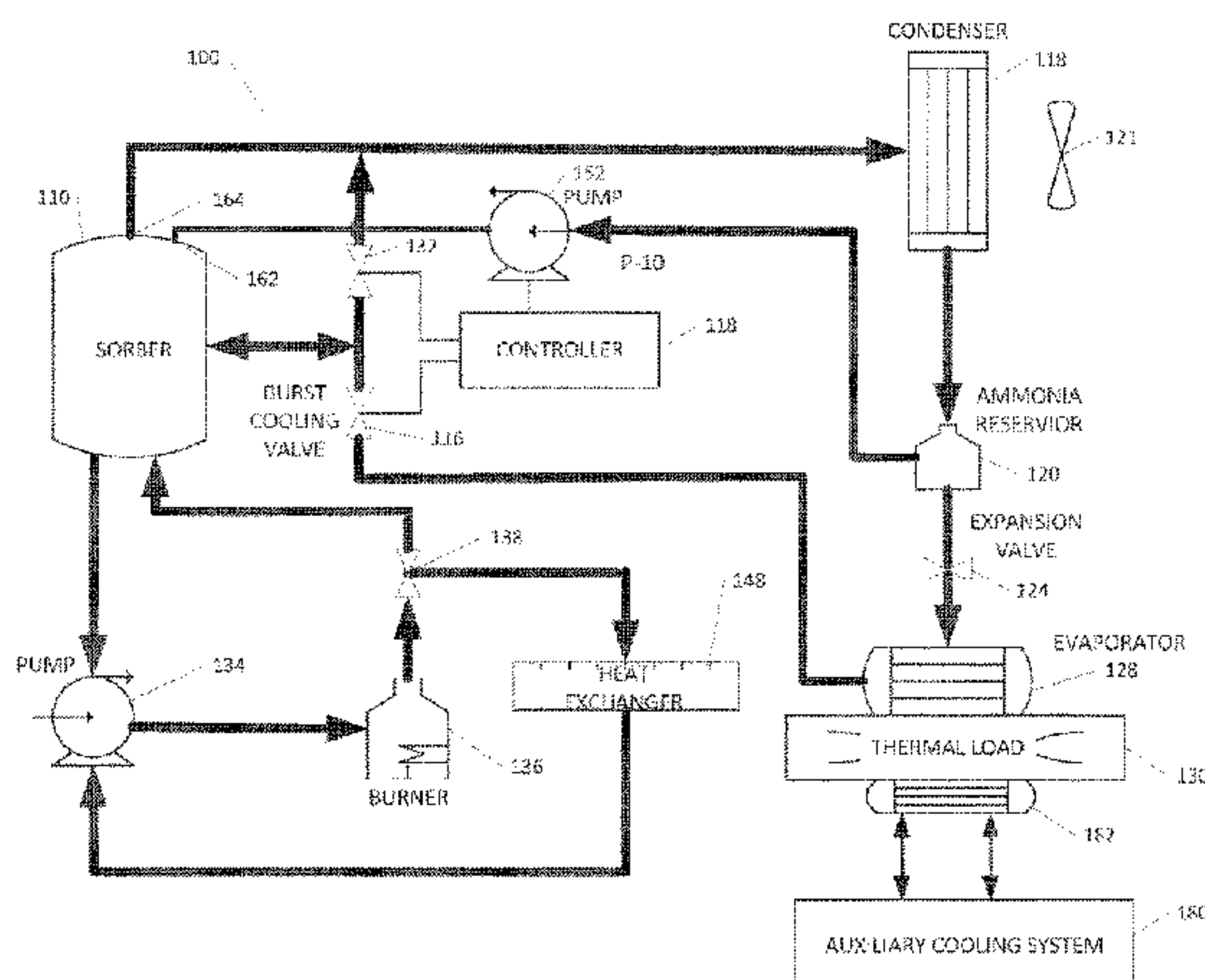
(52) **U.S. Cl.**

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(58) **Field of Classification Search**

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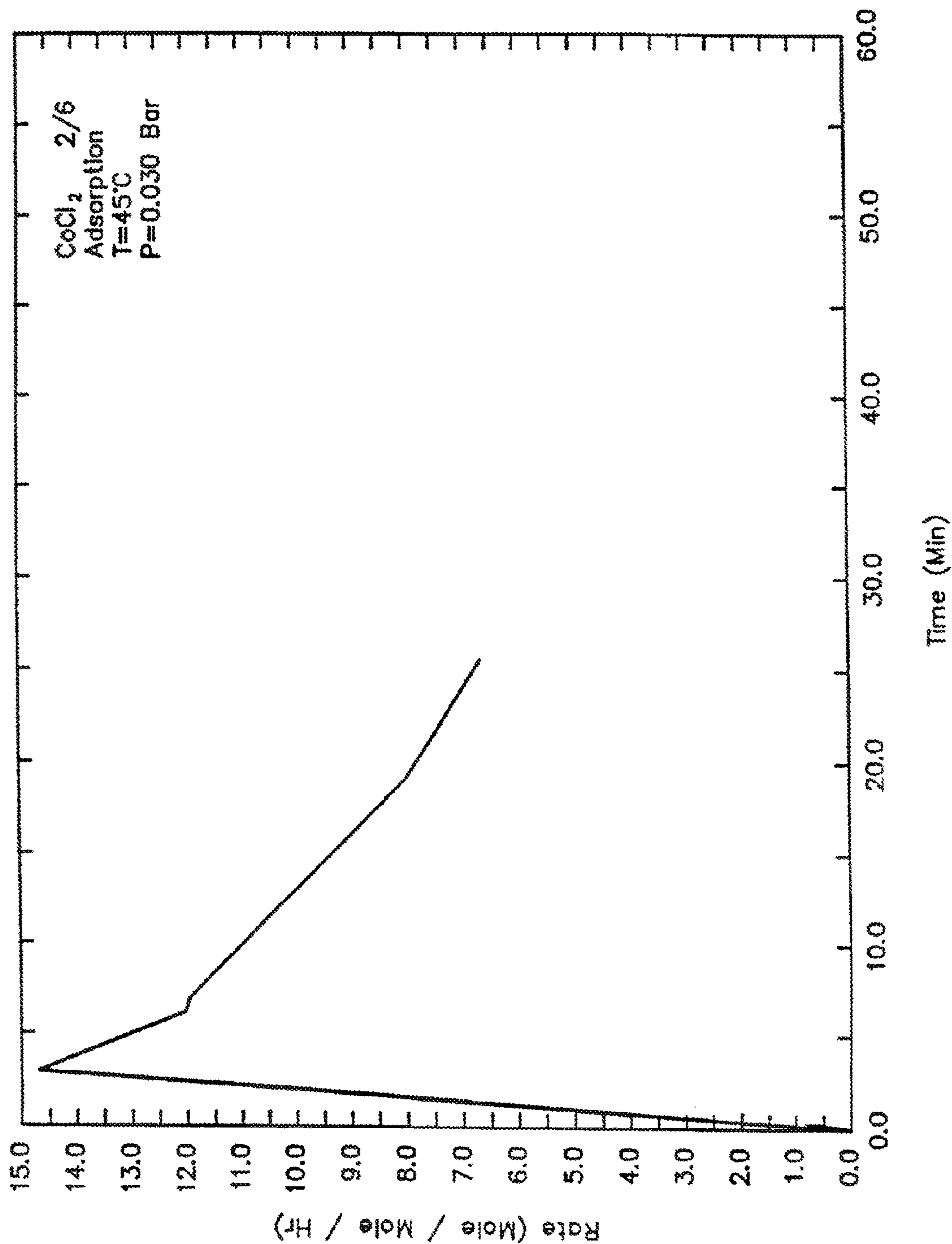


FIGURE 1



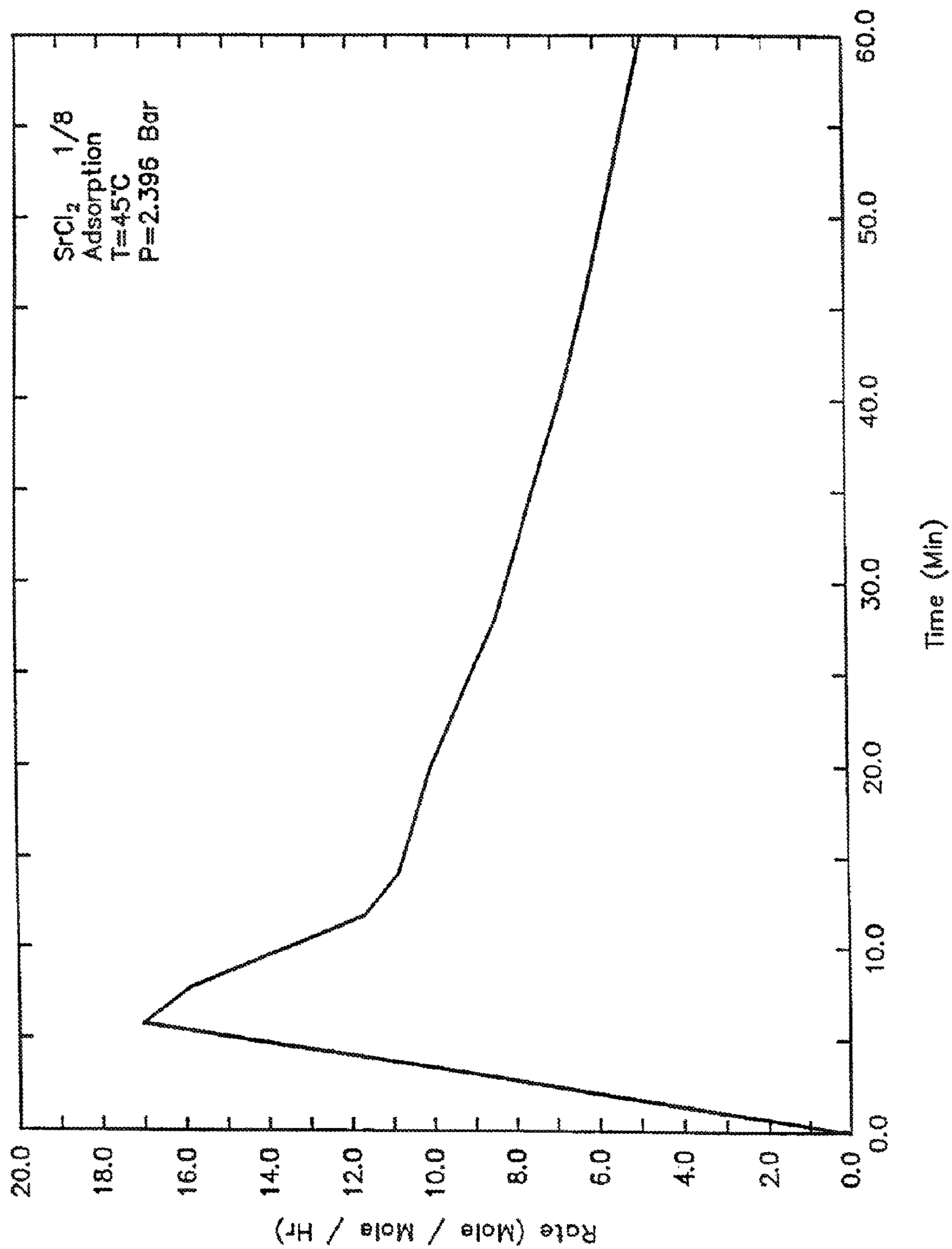


FIGURE 2

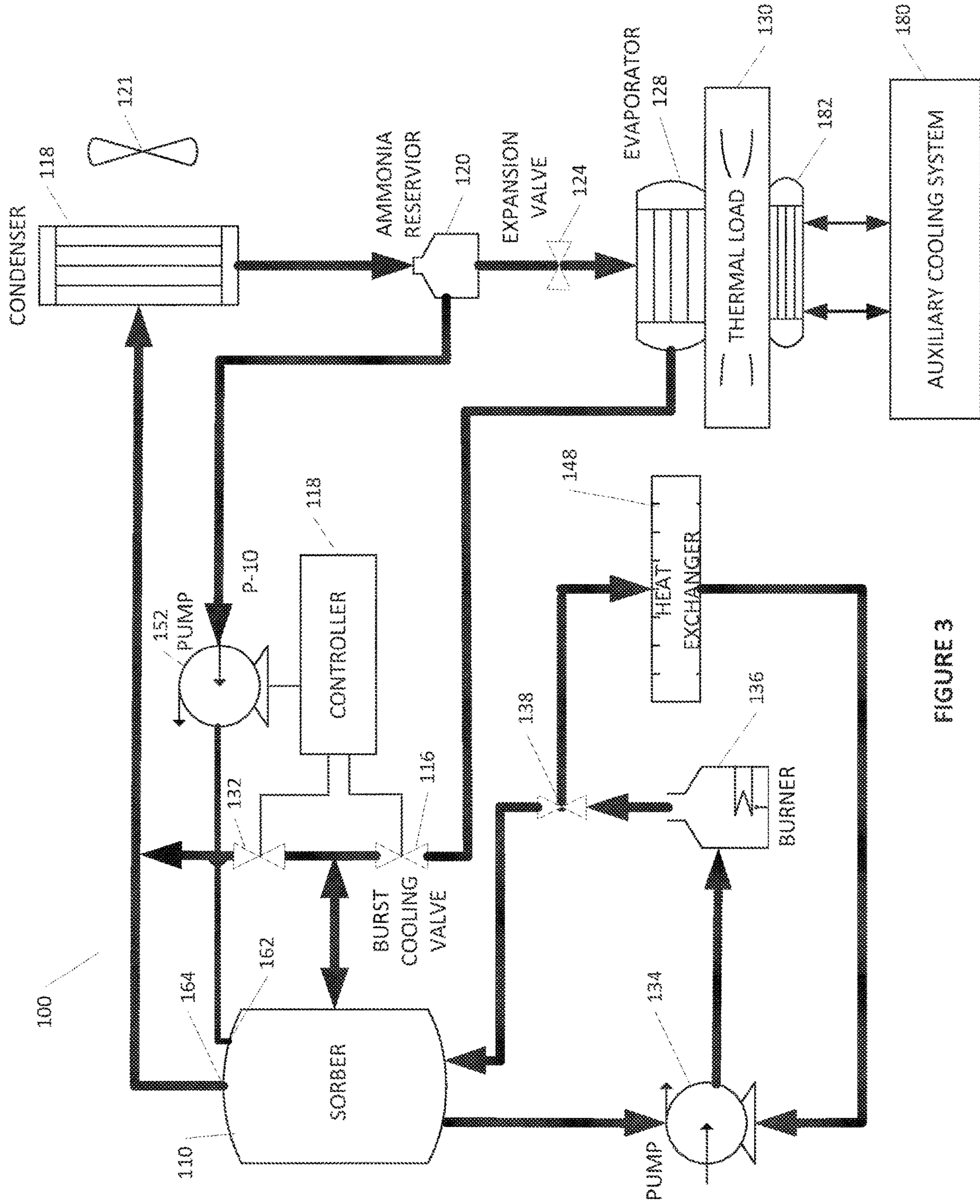


FIGURE 3



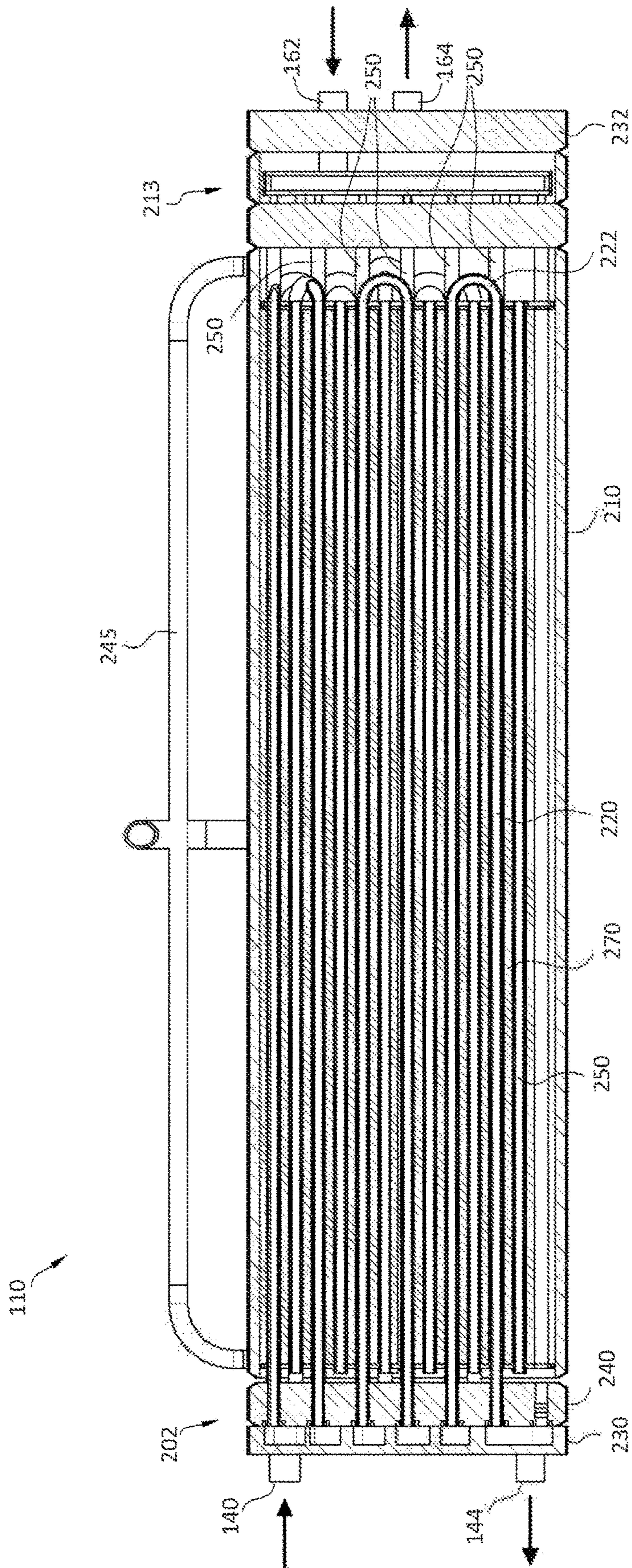


FIGURE 4

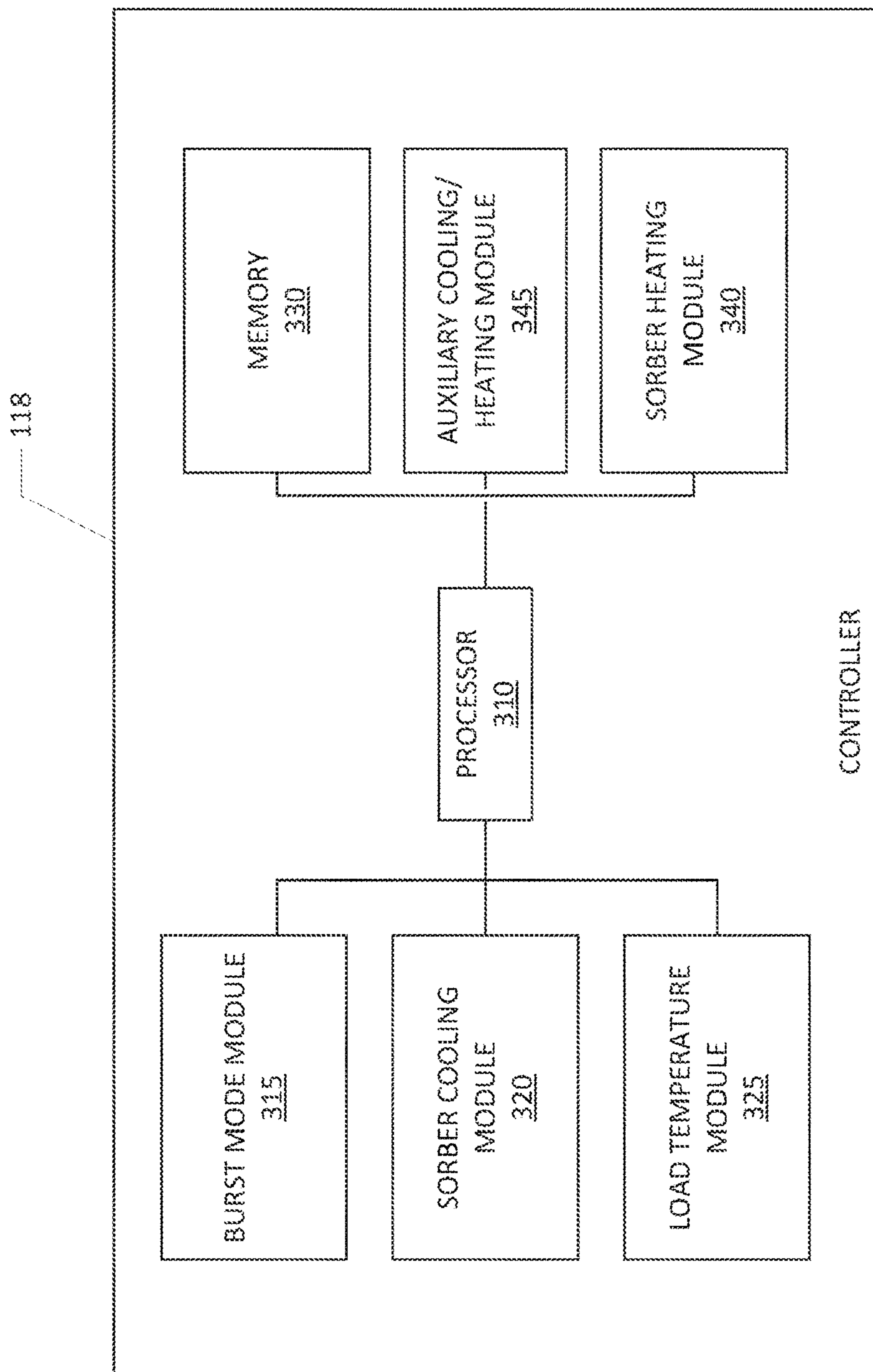


FIGURE 5



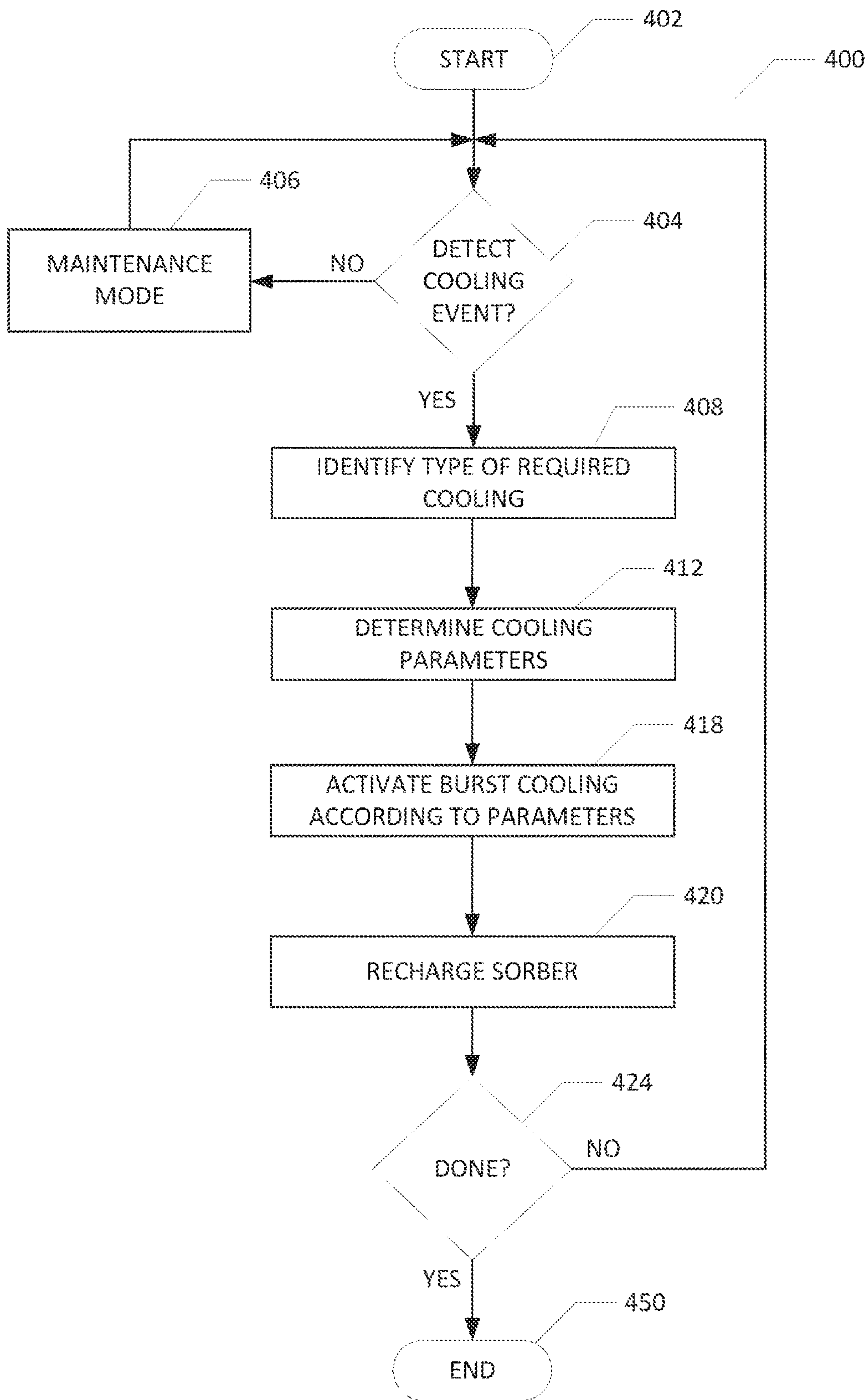


FIGURE 6



**1****INTELLIGENT COOLING FOR DIRECTED  
ENERGY SYSTEMS****CROSS-REFERENCE TO RELATED  
APPLICATIONS**

This application is a divisional filing of U.S. patent application Ser. No. 16/596,573, filed 8 Oct. 2019, which is a continuation application of U.S. patent application Ser. No. 15/451,150, filed Mar. 6, 2017, the entirety of which are both hereby incorporated by reference.

**BACKGROUND**

## Field of the Invention

This disclosure relates generally to sorption refrigeration systems using sorbers and with complex compounds and a sorber gas that are configured to provide rapid cooling features. In particular, features for a rapid pulldown of a thermal load, for example for flash freezing or cooling a fast-rising heat load with an auxiliary cooling/heating system for maintaining the temperature of the thermal load or related environment.

## Description of the Related Art

Adsorption/desorption or also referred to as absorption/desorption reactions between polar gases and certain metal salts yield complex compounds which are the basis for efficient refrigeration, thermal storage, heat pump systems and power systems having high energy density. However, energy density, a measure of the quantity of polar gas adsorbed on the salt, which translates into the amount of work or energy which can be stored in a given amount of the complex compound, is only one parameter to be considered in designing commercially attractive systems.

Of significance, if not greater importance, are the reaction rates between the gas and the complex compound, which result in the time it takes to adsorb and desorb a given amount of the gas into or from the complex compound. Increased or maximized reaction rates result in increased or improved power that can be delivered by the system, i.e., more energy delivered over a period of time, which translates into a greater heating, cooling or power capability of the system.

The reaction rates in these systems are partly a function of how efficiently the gas is distributed to the complex compound. Previous systems have used porous ceramics or cloth to distribute gas to the complex compound. However, the ceramic distributors are fragile and can fracture easily, especially in non-stationary or vibratory environments. For example, ceramic distributors can have difficulty withstanding the vibrations caused by transportation in rough terrain. Cloth distributors have also been found to have some downsides, particularly due to their propensity to clog after multiple cycles. This clogging can increase the pressure drop of the refrigerant in the systems and thereby reduce the performance of the sorber and the absorption system.

**SUMMARY**

The embodiments disclosed herein each have several aspects no single one of which is solely responsible for the disclosure's desirable attributes. Without limiting the scope of this disclosure, its more prominent features will now be briefly discussed. After considering this discussion, and

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particularly after reading the section entitled "Detailed Description of Certain Embodiments," one will understand how the features of the embodiments described herein provide advantages over existing systems, devices and methods for distributing gas in complex compound reactors.

One embodiment is an intelligent cooling system, that includes: at least one sorber comprising a complex compound sorbent configured to absorb and desorb ammonia; at least one heat source thermally connected to the at least one sorber; one or more condensers in fluid communication with the at least one sorber; one or more evaporators in fluid communication with the at least one sorber; a burst mode controller configured to activate a valve to provide a burst of heat absorption to a thermal load adjacent to the evaporator, where the absorption period of the complex compound is between 5 seconds and 300 seconds and the desorption period is between 180 seconds and 15 minutes; and an auxiliary cooling/heating system configured to cool or heat the thermal load or auxiliary equipment.

Another embodiment is a method in an intelligent cooling system of cooling a thermal load that includes: managing an auxiliary cooling system so that the thermal load stays below a target temperature; detecting when to activate a burst mode cooling cycle; activating a valve that allows ammonia to flow into at least one sorber, comprising a complex compound sorbent, wherein the sorber is connected to an evaporator and the activation provides a burst of heat absorption at the evaporator; and controlling the absorption period of the complex compound to between 5 seconds and 300 seconds and the desorption period to between 180 seconds and 15 minutes.

**BRIEF DESCRIPTION OF THE DRAWINGS**

The foregoing and other features of the present disclosure will become more fully apparent from the following description and appended claims, taken in conjunction with the accompanying drawings. Understanding that these drawings depict only several embodiments in accordance with the disclosure and are not to be considered limiting of its scope, the disclosure will be described with additional specificity and detail through use of the accompanying drawings. In the following detailed description, reference is made to the accompanying drawings, which form a part hereof. In the drawings, similar symbols typically identify similar components, unless context dictates otherwise. The illustrative embodiments described in the detailed description, drawings, and claims are not meant to be limiting. Other embodiments may be utilized, and other changes may be made, without departing from the spirit or scope of the subject matter presented here. It will be readily understood that the aspects of the present disclosure, as generally described herein, and illustrated in the figures, can be arranged, substituted, combined, and designed in a wide variety of different configurations, all of which are explicitly contemplated and make part of this disclosure.

FIG. 1 is a line graph showing the absorption rate of ammonia onto  $\text{CoCl}_2$  over time and shows that the absorption rate at the lean end of the coordination sphere, approximately the first up to about five minutes of the reaction, is much faster than outside the lean end of the coordination sphere.

FIG. 2 is a line graph showing the absorption rate of ammonia onto  $\text{SrCl}_2$  over time and shows that the absorption rate at the lean end of the coordination sphere, approxi-



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mately the first up to about five minutes of the reaction, is much faster than outside the lean end of the coordination sphere.

FIG. 3 is a schematic illustration of an embodiment of an intelligent cooling system with an auxiliary cooling system.

FIG. 4 is a schematic illustration of an embodiment of a sorber that is part of the intelligent cooling system of FIG. 3.

FIG. 5 is a block diagram of an embodiment of a controller that is part of the intelligent cooling system of FIG. 3.

FIG. 6 is a flow diagram of an embodiment of a process for activating a burst cooling feature of the intelligent cooling system of FIG. 3.

#### DETAILED DESCRIPTION

Systems and methods are disclosed for rapidly cooling products, devices or other heat loads. Such systems use an ammonia gas sorption system linked to an evaporator to rapidly cool the target product or device. Solid-gas sorption reactions, i.e., adsorption and desorption of the gas on the solid, may be carried out under conditions and in an apparatus intended to yield high power densities. In one embodiment the adsorption period and the desorption period are at different rates to maximize the power density and rapid cooling characteristics of the sorber system.

In one example, the intelligent cooling system includes a burst mode cooling system that may be used for flash freezing products. In flash freezing, a product is brought from one temperature to a second temperature below freezing in a short period of time. In the food industry, flash freezing is performed to maintain the quality of the frozen food. Any other uses, where rapid cooling is desired, is contemplated within this application. Such cases include rapidly heating electronics and laser elements.

In one embodiment the intelligent cooling system includes a burst mode cooling system and an auxiliary cooling/heating system that maintains the temperature of the thermal load or environment between cooling cycles. For example, the auxiliary cooling/heating system may be a vapor compression system that is thermally linked to the thermal load and configured to maintain the thermal load at a predetermined temperature between burst cooling cycles. In some embodiments, the thermal load may need to be within a predetermined temperature range for the burst mode cooling system to efficiently provide rapid cooling. For example, if the thermal load is a flash freezing system for rapidly cooling food products, it may need to maintain a certain temperature to efficiently chill or freeze foods using the burst mode cooling process. The auxiliary cooling/heating system is configured to maintain the thermal load or related environment at a predetermined temperature to help maximize the efficiency of rapidly cooling the thermal load with the burst mode cooling process.

It should be realized that the auxiliary cooling/heating system may not be directly in thermal contact with the thermal load, but may instead be used to cool or heat the environment or equipment directly and/or indirectly relating to the thermal load. For example, the thermal load may be part of a larger system with pumps, motors, and other heat generating equipment. The auxiliary cooling/heating system may be configured to cool this related environment or related equipment. By heating or cooling the equipment adjacent the thermal load, this may help keep the thermal load at a predetermined temperature.

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In one embodiment, the adjacent equipment may be related to a hotel load of a vehicle. In one embodiment, the hotel load is the thermal load caused by all systems on a vehicle other than propulsion. For example, a hotel load of a military transportation vehicle may be the thermal loads caused by radar equipment, inverters, electronics, batteries, cabin loads and the warfighter. Embodiments of the auxiliary cooling/heating system may be configured to thermally regulate these hotel loads to keep them at a predetermined temperature.

Because solid-gas sorption systems operate by adsorbing gas onto the solid complex compounds and then driving the absorbed gas off the complex compound through heating, they may be run on a myriad of energy types. For example, the system may be heated by fossil fuels, such as Diesel or JP-8, electricity, natural gas, solar thermal or any other type of heating system that has enough thermal power to drive the ammonia gas from the complex compound sorbent.

In order to provide the relatively fast absorption rates contemplated by the burst mode cooling system, the system may use one specific complex compound and refrigerant, such as phase change ammonia. In one embodiment, the complex compound sorbent is  $\text{CaCl}_2$ ,  $\text{MgCl}_2$ ,  $\text{CoCl}_2$ ,  $\text{FeCl}_2$ ,  $\text{SrBr}_2$ ,  $\text{SrCl}_2$ ,  $\text{CaBr}_2$  or  $\text{MnCl}_2$  in combination with ammonia ( $\text{NH}_3$ ) as the refrigerant. However, it should be realized that the complex compound may be selected from the following groups of salts:

- (1) an alkaline earth metal chloride, bromide or chlorate salt,
- (2) a metal chloride, bromide or chlorate salt in which the metal is chromium, manganese, iron, cobalt, nickel, cadmium, tantalum or rhenium,
- (3) a double chloride salt selected from  $\text{NH}_4\text{AlCl}_4$ ,  $\text{NaAlCl}_4$ ,  $\text{KAlCl}_4$ ,  $(\text{NH}_4)_2\text{ZnCl}_4$ ,  $(\text{NH}_4)_3\text{ZnCl}_5$ ,  $\text{K}_2\text{ZnCl}_4$ ,  $\text{CsCuCl}_3$ , and  $\text{K}_2\text{FeCl}_5$ ,
- (4) sodium bromide or ammonium chloride, and
- (5) transition metal halides, including zinc chloride.

Other complex compounds can be found in U.S. Pat. No. 4,848,994 issued on Jul. 18, 1989 and incorporated by reference herein for all purposes.

As described below, the system may be configured by an electronic controller to provide a burst discharge for cooling a device or product in a very short period of time. In one embodiment, each absorption period, which provides the burst cooling of the complex compound may be between 5 seconds and 300 seconds. Food process cooling is typical at the high end of the time range while cooling of heat generating laser systems, microwaves, etc. can be at the short or high end. In other embodiments, the absorption period may be between 10-200, 15-150, 20-100, 30-75 or 40-50 seconds. In other embodiments, the absorption period may be less than 200, 175, 150, 125, 100, 75, 50, 25, 10, 15, 7, or 5 seconds long. The absorption period may also be divided into multiple "pulse periods". For example, one absorption period of 25 seconds may be made up of three pulses of absorption for five seconds each, with a five second rest between each pulse. Other numbers of pulses within the absorption period, or number of rest periods are also contemplated. For example, the number of pulses within an absorption period may be 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15 or more pulses per absorption period. The pulse periods may be between 5-10, 5-20 or 5-30 seconds long each in some embodiments.

The controller may be configured in many ways to activate a burst mode cooling cycle. In one embodiment, the controller is any electronic device or apparatus that activates, modulates, or deactivates the flow of refrigerant or



heat transfer fluids in the system. The controller may also be any electronic device or apparatus that controls heat at a burner within the system. In one embodiment, the controller is linked to a temperature sensor and activates a burst mode cooling cycle when the temperature sensor reaches a predetermined target temperature. The temperature sensor may be thermally linked to the thermal load being cooled to that when the thermal load reaches the predetermined target temperature, a cooling cycle is begun. Alternatively, the controller may be electronically linked to an activation signal, that triggers a burst mode cooling cycle. The activation signal may be controlled by a predictive process that senses a variety of data and then predicts when to activate a cooling cycle. For example, the controller may sense the present temperature of the thermal load, the time since the last activation, and the state of other equipment of devices linked to the thermal load. Using this data, the system may activate a burst mode cooling cycle just before the thermal load starts to heat. For example, if the thermal load is a flash freezing system, the controller may detect when the system may need to begin freezing food or other products. Just prior to the freezing being needed, the system initiates a burst of cooling so that the thermal load is cooled at the appropriate time. In some embodiment, the controller may activate a cooling cycle 1, 2, 3, 4, 5, 6, or 10 seconds in advance of a determined cooling event.

Using the lean end of the coordination sphere yields faster rates of absorption with the option of pulsing within each absorption period in even faster burst reaction rates. As used herein the coordination sphere is a central metal ion and its coordination ligands, in the subject coordination sphere, but not counting ligand molecules of a possible lower coordination sphere. In one embodiment the lean end of the coordination sphere is the lower 50% of the subject coordination sphere where less than 50% of the possible coordinating ligands, such as ammonia, are bound to the central metal ion. In other embodiments, the lean end of the subject coordination sphere may be the lower 30%, 25% or 20% of the coordination sphere. For example, the highest rates of ammonia absorption are when the complex compounds in the sorber have the most absorption sites available for bonding to ammonia molecules.  $\text{SrCl}_2$  has eight available absorption sites for ammonia. The first coordination sphere is the 0-1 sphere, the second is the 1-8 sphere, the latter being of interest in the majority of embodiments of the subject matter of this disclosure. The 0-1 and 1-8 spheres are the theoretical numbers not accounting for solid-solid solution effects that narrow the window of thermodynamic monovariacy. In the case of  $\text{SrCl}_2$ , the effective range of monovariacy in which the vapor pressure is independent of the ligand concentration is about 1.8-7.5. Thus, the time required for a mole of  $\text{SrCl}_2$  to go from 1.8 mole of absorbed ammonia to 2.8 moles of ammonia in that second coordination sphere is much shorter than for one mole of  $\text{SrCl}_2$  to go from 2.8 moles of absorbed ammonia to 3.8 moles of absorbed ammonia. However, in certain lower temperature ambient conditions, particularly less than 20° C., it may be preferable to start with less than 1.8 moles of ligand, and start the absorption within the 0-1 sphere, the first coordination sphere. For  $\text{SrCl}_2$ , the lean end of the coordination sphere may be the lower 20% of the coordination sphere. This is similar for the majority of other compounds. Embodiments of the intelligent cooling system described herein are tuned to keep the complex compounds in the sorber at their leanest, with the fewest number of moles of ammonia, in order to allow higher reaction rates and result-

ing shorter reaction times for each absorption reaction, thus providing higher cooling power.

In one embodiment, the system is designed to absorb ammonia in the "leanest" portion of each complex compound's absorption profile. Thus, in embodiments of this system, if  $\text{SrCl}_2$  is the compound, and each mole of  $\text{SrCl}_2$  is capable of absorbing eight moles of ammonia, the system will be configured to have an absorption cycle that preferably absorbs ammonia when 3.5 or three or less moles of ammonia are absorbed to each mole of  $\text{SrCl}_2$ . If more than three moles of ammonia are absorbed onto each mole of  $\text{SrCl}_2$  then the controller may instruct the system to perform a sorber heating cycle to drive off the bound ammonia and reset the complex sorbent to be back into its preferred range of fewer than three moles of ammonia per mole of  $\text{SrCl}_2$  for another round of burst mode cooling.

Similarly, if  $\text{MnCl}_2$  is the sorbent and can absorb up to six molecules of ammonia for each molecule of  $\text{MnCl}_2$  with the relevant coordination sphere being the 2-6 mole sphere, then the system will be configured to have an absorption cycle to preferably absorb ammonia only when each mole of  $\text{MnCl}_2$  has about 3.5, 3 or fewer moles of absorbed ammonia molecules, absorbing from about 2 moles of ammonia per mole of  $\text{MnCl}_2$  to 3.5 moles of ammonia per mole of  $\text{MnCl}_2$ .

If  $\text{CaBr}_2$  is the sorbent then the system may be configured to have an absorption cycle wherein ammonia is absorbed onto the  $\text{CaBr}_2$  sorbent when less than about 3.5 moles of ammonia are already bound, absorbing from about 2 moles of ammonia per mole of  $\text{CaBr}_2$  to 3.5 moles of ammonia per mole of  $\text{CaBr}_2$ . In some embodiments, the system may be configured to only absorb ammonia onto a  $\text{CaBr}_2$  sorbent when there are less than about 3 moles of ammonia already bound to the  $\text{CaBr}_2$  sorbent. These configurations can be managed by using the controller to tune the adsorption and desorption times to be active when the compound can be loaded with ammonia most efficiently.

In one embodiment, the temperature change/desorption period may be between 1.80 seconds and 15 minutes in order to reload the system. In some embodiments, the desorption period is less than 5, 4, or 3 minutes, or less.

FIG. 1 shows the results of an experiment wherein the rate (mole/mole/hr) of ammonia binding to a  $\text{CoCl}_2$  sorbent in a heat exchanger was measured over time at a pressure of 0.030 Bar and a constant temperature of 45° C. It was found that the rate of ammonia absorption was much faster during the initial reaction when  $\text{CoCl}_2$  was at the lean end of the coordination sphere and few moles of ammonia were bound to each mole of  $\text{CoCl}_2$ . As shown, after about the first four minutes of absorption the rate reached over 14.5 moles of ammonia being added to each mole of  $\text{CoCl}_2$  per hour. However, after the first about four minutes, the rate of ammonia addition started to decrease as ammonia bonding positions on each mole of  $\text{CoCl}_2$  were taken up by earlier reactions. Higher differential temperatures and pressures yield much higher rates, but the ratio of reaction rates between the lean and rich end of the coordination sphere either remains the same or gets even more pronounced.

FIG. 2 shows the results of an experiment wherein the rate (mole/mole/hr) of ammonia binding to a  $\text{SrCl}_2$  sorbent in a heat exchanger was measured over time at a pressure of 2.396 Bar and a constant temperature of 45° C. It was found that the rate of ammonia absorption was much faster during the initial reaction when  $\text{SrCl}_2$  was at the lean end of the coordination sphere and few moles of ammonia were bound to each mole of  $\text{SrCl}_2$ . As shown, after about the first six minutes of absorption the rate reached over 17 moles of ammonia being added to each mole of  $\text{SrCl}_2$  per hour.



However, after the first about six minutes, the rate of ammonia addition started to decrease as ammonia binding positions on each mole of  $\text{SrCl}_2$  were taken up by earlier reactions. As is the case with all complex compounds of this material class, higher differential temperatures and pressures yield much higher rates, but the ratio of reaction rates between the lean and rich end of the coordination sphere either remains the same or becomes even more pronounced

Optimum reaction rates for embodiments are also dependent on a number of independent parameters including adsorbent density, the mass diffusion path length, the heat or thermal diffusion path length, as well as the thermodynamic operating conditions. The latter include the overall process conditions i.e., the specific temperature and pressure conditions in which the process is carried out, the differential pressure or i.e., the difference between the operating or system pressure and the equilibrium pressure of the complex compound, and the approach temperature or  $\Delta T$ . One consequence of performing adsorption and desorption reactions at relatively fast speeds to provide burst cooling is that the approach temperature may be higher than normal. In embodiments of the invention, the approach temperature may be from  $15^\circ\text{K}$  and  $35^\circ\text{K}$  to cause a faster desorption of the ammonia.

In one embodiment, when the reactor is configured with an approach temperature for desorption of the ammonia at relatively high temperatures of  $15^\circ\text{K}$  and  $30^\circ\text{K}$ , the system may stop heating prior to the end of the desorption cycle. For example, the controller may instruct the system to stop heating the desorber 2, 3, 4, 5, 10, 20, 30 or more seconds before the desorption reaction is ending. This allows the ammonia to continue to desorb from the complex compound, but also allows the desorber to be cooled in order to get ready for the next round of absorption. The embodiment allows the desorber to begin cooling in advance of the next refrigeration cycle in the system and provides a higher overall efficiency in cycling the sorber for the next round of burst mode cooling.

In one embodiment the sorber is also configured to stop being cooled in advance of the end of the absorption cycle in order to prepare the sorber for the next cycle of heat. For example, the controller may stop circulating cooling fluid to the sorber 2, 3, 4, 5, 10, 20, 30 or more seconds before the reaction is ending. In one embodiment, the cooling loop of the system often comprising glycol and water or other suitable heat transfer fluids may be turned off in order to allow the absorber rise in temperature before the next reaction cycle begins. In other embodiments, the cooling loop may use ammonia or other phase change fluid to cool the sorber.

Generally, the reactor should be designed to have a relatively low thermal mass. A reactor with more thermal mass takes longer to heat up and cool down. Embodiments of this invention include reactors that can provide efficient bursts of cooling, which means that the ability to rapidly heat and cool are one consideration of the reactor design. One way to measure the thermal mass is the ratio of the total weight in kilograms of the reactor (including shell, fins, complex compounds, etc.) to the weight in kilograms of the complex compounds (salt) within the reactor. In one embodiment, this ratio is less than 7:1 and more preferably less than 6:1, 5:1, 4:1 or 3:1. In one embodiment, the thermal mass of the reactor is reduced by manufacturing portions of the reactor out of advanced materials such as aluminum, titanium, advanced fiber composites, or other similar light-weight materials.

Embodiments may be part of a system configured to cool devices such as directed energy weapons systems, such as laser, electro-laser and microwave systems which rapidly heat when activated. These types of directed energy weapons systems may include additional ancillary mechanical or electrical equipment or components that may need to be cooled in order to operate the weapons system efficiently. Such additional equipment may include radar systems, batteries, power modules, generators, pumps, motors and other equipment that is ancillary to the main weapons system. In particularly warm environments, such as the desert, these additional components may work more efficiently by being cooled prior to use. Embodiments provide an auxiliary cooling/heating system that is configured to cool or heat these additional components to a predetermined temperature, or within a temperature range, so that they operate efficiently in many types of environments.

Embodiments could also be part of rapid freezing systems for any industry such as the food and beverage industries. In this industry, the auxiliary cooling/heating system may be configured to cool industrial or factory equipment related to the burst mode cooling process. For example, the auxiliary cooling/heating system may pre-cool food to a particular temperature before the food is flash frozen using the burst mode cooling system. In other embodiments, the auxiliary cooling/heating system may cool the adjacent or related factory equipment that is part of the flash freezing process so that equipment continues to function properly within the burst mode cooling process.

FIG. 3 shows one exemplary intelligent cooling system **100** that has a complex compound based sorber **110** that is designed to absorb and desorb ammonia. Additional details on the sorber **110** can be found with reference to FIG. 4 below. The cycle begins when a burst cooling valve **116** is opened under control of an electronic controller **118**. Opening the valve **116** allows condensed ammonia stored in an ammonia reservoir **120** to rapidly expand through an expansion valve **124** and move through an evaporator **128**. As the expanding ammonia liquid changes to a gas and moves through the evaporator **128** it absorbs heat from an adjacent thermal load **130**. This rapidly cools the thermal load **130**. The ammonia liquid that was evaporated to gas by the thermal load **130** moves through the open burst cooling valve and into an inlet/outlet **131** to the sorber **110** where it becomes absorbed onto the complex compounds within the sorber **110**.

After the burst cooling is completed, the system needs to drive the absorbed ammonia gas from the complex compounds and so activates a heating pump **134** that can circulate heated thermal media, such as an ethylene glycol and water mixture into the sorber. In one embodiment, the thermal media is approximately 30% ethylene glycol in water, however, other compositions of thermal media are also within the scope of embodiments of this invention. For example, the thermal media may be SYLTHERM™ (Dow Corning Corporation, Midland, Mich.), PARATHERM™ (Paratherm, King of Prussia, Pa.) or similar heat transfer fluids.

Activating the heating pump **134** moves the thermal media into a burner **136** that heats the media to a target temperature. In one embodiment the target temperature is between  $125^\circ\text{C}$ . and  $140^\circ\text{C}$ . In another embodiment the target temperature is  $130^\circ\text{C}$ . The heated thermal media is then pumped through a control valve **138** and into a hot thermal media inlet **140** within the sorber **110**. The thermal media flows out of the sorber **110** from a hot thermal media outlet **144** and back to the heating pump **134**. The heated



thermal media circulates through the sorber 110 for a predetermined period of time to drive off the absorbed ammonia gas so that the sorber can enter another cycle of absorbing ammonia onto its complex compound surface.

To run the heated thermal media efficiently through the sorber 110, the system also includes a heat exchanger 148 that can have heated thermal media flowing through it during times when the sorber 110 does not need to be heated. The control valve 138 is controlled by the controller to switch the flow of thermal media to the heat exchanger 148 when the sorber does not need to be heated, and to the sorber 110 when it's time to heat the sorber within the refrigeration cycle.

The heated ammonia gas moves out the inlet/outlet 131, through an ammonia gas return valve 132, and flows towards a condenser 119 to start an additional cycle. The controller 118 controls the burst cooling valve 116 and the ammonia gas return valve 132 to that ammonia gas enters and exits the sorber properly during each cycle. At the condenser 119, the ammonia gas is cooled by a fan 121 and condensed towards a liquid state before flowing into an ammonia reservoir 124. The ammonia reservoir acts as a holding container for pressurized ammonia gas or liquid prior to being recirculated to the sorber, or used for burst mode cooling.

After the sorber is heated to drive off absorbed ammonia, the sorber needs to cool to be able to absorb ammonia for the next round in the refrigeration cycle. To help cool the sorber, the system includes a cooling pump 152 that circulates ammonia from the ammonia reservoir 120 into a series of cooling thermal media lines within the sorber 110. The cooling pump 152 is activated by the controller 118 and draws ammonia from the reservoir 120 flows it into a thermal media inlet 162 and out a thermal media outlet 164. The ammonia absorbs heat from inside of the sorber 110 and then recirculates that heated ammonia to the condenser 119 to help cool down the sorber for the next round of absorption.

Also communicating with the thermal load 130 is an auxiliary cooling/heating system 180 that includes an auxiliary evaporator 182. The auxiliary cooling/heating system 180 can be any type of well-known cooling system, such as a vapor compression based system or complex compound sorbent based system. In one embodiment, the auxiliary cooling/heating system 180 is controlled by the controller 118. The controller 118 can be configured, or programmed with instructions for managing the temperature of the thermal load 130 between burst mode cooling cycles. For example, the auxiliary cooling/heating system 180 may include one or more environmental or temperature sensors that detect the temperature of the thermal load. The controller may receive data relating to the temperature of the thermal load, or its local environment or adjacent equipment, and from that data increase or decrease the amount of cooling from the auxiliary cooling/heating system 180.

It should be realized that the auxiliary cooling/heating system 180 does not need to be located directly adjacent to the thermal load, but instead may be configured to manage the temperature of equipment that is ancillary to the thermal load 130. For example, the auxiliary cooling/heating system 180 may be configured to cool a room of mechanical equipment that is linked to the thermal load 130.

Additional details on the sorber 110 are shown in FIG. 4. The sorber 110 includes a lower end 202 and an upper end 213 that is opposite the lower end 202. The ends 202 and 213 facilitate moving thermal transfer media through a set of heat transfer tubes 220 that traverse the interior of the sorber 110. The lower end 202 includes the hot thermal media inlet

140 and an outlet 144 that communicate with a first circuit of the heat transfer tubes 120. The upper end 213 includes the cold thermal media inlet 162 and an outlet 164 that communicate with a second circuit of the heat transfer tubes 120. The sorber 110 may include other inlets and/or outlets as needed to move thermal transfer media and/or sorber gas through the system. The various inlets and outlets may provide piping or other channels through which the sorber gas and/or refrigerant may flow.

The sorber 110 has an outer shell 210 that is an elongated cylindrical layer that surrounds and encapsulates a complex compound sorbent 270 disposed within the interior of the sorber 110. In some embodiments, the shell 210 may have other suitable shapes and may be composed of more than one layer. The shell 210 may be formed from a rigid material such as a metal or metal alloy, but it may be formed from other suitable materials as well. Among other things, the shell 210 acts as a barrier for the sorbent 270 to prevent the sorbent 270 from expanding radially outward when the sorber 110 is pressurized.

The lower end 202 of the sorber 110 includes a hot water box 230 and a feed box 240. In some embodiments, the hot water box 230 is a fluid bonnet. The hot water box 230 contains a fluid, such as ethylene glycol/water that is then distributed by the feed box 440 through the heat transfer pipes 220 which run adjacent the complex compound sorbent and are used to heat the sorbent to release the ammonia gas.

Similarly, the upper end 213 of the sorber 110 includes a cold box 232. The cold box 232 may be a cooling fluid bonnet. The cold box 232 provides cool fluid, such as ammonia from the reservoir 120 to a second circuit of heat transfer tubes 120 within the sorber 110 to cool the sorber 110 between refrigeration cycles.

By flowing a heat transfer medium 120 through the heat transfer pipes 220, which are adjacent the complex compound material, heat may be transferred to and from the sorbent material. The heat transfer pipes 220 may have bends 222, which may be "U" shaped bends. The bends 222 may be located on either or both of the ends 202, 213 of the sorber 110. In some embodiments, the bends 222 are U-shaped and located near the upper end 213 of the sorber 110. Therefore, in some embodiments the sorber has a dual bonnet design with two circuits for heating and cooling the sorbent material within the sorber 110.

The sorber 110 includes a sorber gas pipe 245 for flowing the sorber gas to and from the sorber 110. The sorber gas flows from the pipe 245 and into the sorber 110 in various locations. In some embodiments, there may only be one location. As shown, the pipe 245 connects with the sorber 110 at three locations along the side of the sorber 110. The pipe 245 may also connect with the sorber 110 in other locations. The sorber gas flows from the pipe 245 and into a set of porous gas distribution tubes 250. In some embodiments, sorber gas flows from the pipe 245 and into compartments (not shown) in the sorber 110 and then into the gas distribution tubes 250. A variety of configurations are possible, and these are just some examples. One embodiment of a sorber can be found in U.S. Patent Publication 2016/0238286 A1 published on Aug. 18, 2016 and incorporated herein by reference for all purposes.

FIG. 5 shows an illustration of the controller 118, which is programmed with instructions to control operations of the system 100. The controller 118 includes a processor 310 which may be any type of well-known microprocessor or microcontroller that is capable of managing the valves, fans and other components of the system 100. The processor 310



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is connected to a Burst Mode Module **315** which includes instructions for activating a burst of cooling to the thermal mode under certain predetermined conditions. In one embodiment, the Burst Mode Module **315** is programmed to activate the burst cooling valve **116** to rapidly cool the thermal load **130** when a predetermined signal is received by controller **118**. The signal may be an activation signal from a system connected to the thermal load. For example, if the thermal load is a piece of machinery or equipment, it may send a signal to activate the burst mode cooling just prior to the machinery or equipment starting a rapid heating cycle. In one embodiment the machinery or equipment may be weapons or other equipment that rapidly heats upon activation. In one embodiment the weapon may be a laser or microwave type weapon that heats in relatively short bursts as the weapon is discharged. With each discharge the weapon system may trigger the intelligent cooling mode of the system **100** in order to reduce the temperature of the weapon system. In another embodiment, the machinery or equipment may be configured to absorb heat from a mechanical or electrical system that rapidly heats when activated. That mechanical or electrical system may be programmed to trigger the burst mode cooling whenever bursts of energy are used within the mechanical or electrical system so that additional cooling of specific components is warranted.

The controller **118** also includes an auxiliary cooling/heating module **345** that includes instructions for managing the functions of the auxiliary cooling/heating system discussed above. The auxiliary cooling/heating module **345** may include instructions for reading data from temperature or other environmental sensors and determining the proper parameters for cooling or heating the thermal load or adjacent systems. For example, if the auxiliary cooling/heating module **345** receives data showing that the thermal load is above 40° C. it may begin a cooling cycle to reduce the temperature of the thermal load back down to a target temperature. Similarly, if the auxiliary cooling/heating module **345** determines that the thermal load is below, for example, 5° C. it may initiate a heating cycle to increase the temperature of the thermal load up to a target temperature. In one embodiment, the auxiliary cooling/heating module **345** maintains the temperature of the thermal load or ancillary equipment within the range of 5° C. to 40° C. In another embodiment, the auxiliary cooling/heating module **345** maintains the temperature of the thermal load or ancillary equipment within the range of 20° C. to 30° C. However, embodiments are not limited to only these temperature ranges. The auxiliary cooling/heating module **345** may be designed to maintain the temperature of the thermal load or ancillary equipment to be above its minimum equipment design operating temperature in cold climates for an efficient start-up. Similarly, the auxiliary cooling/heating module **345** may be designed to cool the thermal load or ancillary equipment to be below the equipment's maximum design operating temperature at any ambient temperature if the equipment generates heat. This allows the equipment to be placed in relatively hot ambient environments, such as the desert, where the ambient conditions alone may require cooling of the equipment to be within the range of, for example, 5° C. to 40° C.

Other embodiments include an auxiliary cooling/heating module **345** that maintains the temperature of the thermal load or ancillary equipment in order for efficient burst cooling of the thermal load to occur. Of course, the system is not limited to only managing thermal loads at these temperature parameters. The auxiliary cooling/heating module **345** may detect when temperatures of a thermal load are

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above 5° C., 10° C., 15° C., 20° C., 25° C., 30° C., 35° C., 40° C. or more before activating the auxiliary cooling/heating system. In some embodiments the auxiliary cooling/heating module **345** is also configured to maintain operating temperatures of equipment that is a subsystem, of linked system to the thermal load. For example, the thermal load may be adjacent to, or electronically linked with, electronic subsystems, such as radar, electronic or power inverters, generators, high-capacity batteries, cabin/enclosures and warfighter cooling systems. The auxiliary cooling/heating module **345** may be designed to maintain the operating temperatures of each of these ancillary devices or systems in addition to maintaining the operating temperature of the thermal load and adjacent equipment.

The auxiliary cooling/heating module **345** may also gather data from other sources, such as through a network connection to determine the predicted environmental temperature for the day. For example, the auxiliary cooling module **345** may receive the predicted daytime high temperature from a weather service across a network and use that data to ensure that the thermal load or other ancillary components of the target system remain cool to a predetermined target temperature.

The controller **118** also includes a sorber cooling module **320** that controls cooling of the sorber after the sorber has been heated to drive the absorbed ammonia from the complex compound sorbent. The sorber cooling module **320** may work in conjunction with the ammonia gas return valve **132** which helps circulate cool ammonia vapor/liquid through the sorber **110** to cool the sorber to a target temperature before initiating a burst mode cooling cycle.

The controller **118** also has a load temperature module which monitors the temperature of the thermal load **130** attached to the evaporator **128**. In one embodiment, the load temperature module **325** activates a burst cooling mode when the temperature of the thermal load **130** reaches a predetermined load temperature. For example, when the temperature of the thermal load is above 10° C. and below 50° C., then the load temperature module activates the burst cooling valve to cool the thermal load below its target temperature. In other embodiments, the burst cooling valve may be activated when the temperature of the thermal load is above 15° C. and below 45° C. or above 20° C. and below 40° C. Of course, embodiments are not limited to performing only a single burst cooling procedure. During activation, the thermal load, or an attached weapons system, may request multiple burst mode cooling operations to maintain the temperature of the thermal load below a certain target temperature.

In one embodiment the controller may manage the variable speed operation of various pumps and fans within the system based on the temperature of the thermal load. For example, as the temperature of the thermal load, or surrounding environment, increases the speed of pumps and fans within the system may also increase. Similarly, as the temperature of the thermal load, or surrounding environment decreases, the controller may slow the speed of the pumps and/or fans.

The controller may also include a sorber heating module **340** which is configured to heat the sorber **110** at the proper time in the cooling cycle to drive the ammonia from the complex compound sorbent. The controller may be connected to the valve **138** which determines if the heated liquid flowing through the burner **136** is directed into the sorber **110** or instead to the heat exchanger **148**. When the sorber heating module **340** determines that its time to drive off the



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ammonia gas it can open the valve 138 which allows a heated aqueous mixture to flow through the sorber and heat the sorbent material.

Each of the instructions may be stored in a memory 330 that is connected to the processor 310 within the controller 118.

FIG. 6 is a flow diagram of a process 400 for performing a burst mode cooling of a thermal load. The process 400 begins at a start state 402 and then moves to a decision state 404 wherein a determination is made whether a cooling event has been detected. A cooling event may be, for example, the determination that the thermal load has reached a target temperature. Another cooling event may be, for example, the receipt of a signal from a machine or equipment attached to the thermal load that it will require burst cooling at an upcoming time. If a determination is made at the decision state 404 that no cooling event has been detected, the process 400 moves to a state 406 where the system enters a maintenance mode where the cooling system can prepare for a next cooling event. For example, the system may use the maintenance mode to drive off ammonia bound to the sorbent from a prior burst cooling event. The system may also start to circulate some of the ammonia from the ammonia reservoir through cooling pipes within the sorber to reduce the temperature of the sorber so it can be prepared for an additional burst cooling procedure. The system may perform other measures within the sorber or system to prepare for a future burst mode cooling procedure. Once the maintenance mode is complete at the state 406, the process 400 returns to the decision state 404 to wait until a cooling event is detected.

If a cooling event is detected at the decision state 404, the process 400 moves to a state 408 wherein the type of required cooling is identified. For example, the system may activate longer or shorter bursts of cooling depending on the type of cooling required by the target load or other machine or equipment. Once the type of cooling is identified at the state 408 the process 400 moves to a state 412 wherein the cooling parameters are determined. The cooling parameters may be the number of burst modes to activate, the over length of the cooling required or any other parameter necessary for the system to properly cool the thermal load.

The process 400 then moves to a state 418 wherein the burst cooling is activated by opening the burst cooling valve 116 according to the determined cooling parameters. After the burst cooling has completed the process 400 moves to a state 420 wherein the sorber is recharged by heating the sorbent to drive off the ammonia that has bound at the prior state. The process 400 then moves to a decision state 424 to determine if the cooling process is completed, and if not then the process 400 returns to the decision state 404 wherein the process 400 waits to detect another cooling event. If the overall process is complete at the decision state 424, then the process terminates at an end state 450.

Headings are included herein for reference and to aid in locating various sections. These headings are not intended to limit the scope of the concepts described with respect thereto. Such concepts may have applicability throughout the entire specification.

The previous description of the disclosed implementations is provided to enable any person skilled in the art to make or use the present invention. Various modifications to these implementations will be readily apparent to those skilled in the art, and the generic principles defined herein may be applied to other implementations without departing from the spirit or scope of the invention. Thus, the present invention is not intended to be limited to the implementa-

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tions shown herein but is to be accorded the widest scope consistent with the principles and novel features disclosed herein.

While the above description has pointed out novel features of the invention as applied to various embodiments, the skilled person will understand that various omissions, substitutions, and changes in the form and details of the device or process illustrated may be made without departing from the scope of the invention.

What is claimed is:

1. A method of cooling a directed energy apparatus, the method comprising:

managing an auxiliary cooling system to maintain the directed energy apparatus below a target temperature; detecting when to initiate an absorption cycle of a thermal sorption system, wherein the thermal sorption system is in thermal communication with the directed energy apparatus; and

initiating the absorption cycle, in response to detecting when to activate the absorption cycle, wherein the absorption cycle comprises a plurality of refrigerant pulses, with each pulse within the absorption cycle including a pulse of refrigerant followed by a rest period.

2. The method of claim 1, wherein detecting when to initiate the absorption cycle comprises detecting a thermal load.

3. The method of claim 1, wherein detecting when to initiate the absorption cycle comprises detecting an activation of the directed energy apparatus.

4. The method of claim 1, wherein initiating the absorption cycle comprises initiating the absorption cycle in advance of activation of the directed energy apparatus.

5. The method of claim 1, wherein the plurality of refrigerant pulses comprises two or more refrigerant pulses per absorption cycle.

6. The method of claim 1, wherein each refrigerant pulse of the plurality of refrigerant pulses lasts for a pulse period of 5-30 seconds.

7. The method of claim 6, wherein the pulse period is 5-10 seconds.

8. The method of claim 1, wherein the rest period is at least 5 seconds between pulses.

9. The method of claim 1, wherein the absorption cycle of a complex compound sorbent of the thermal sorption system is between 5 seconds and 300 seconds.

10. The method of claim 1, wherein the directed energy apparatus is a directed energy weapons system that heats in relatively short bursts as the directed energy weapons system is discharged.

11. The method of claim 10, wherein the directed energy weapons system comprises a laser weapon system, electro-laser weapon system or microwave weapon system.

12. The method of claim 10, wherein the auxiliary cooling system comprises a vapor compression cooling system.

13. A system for cooling a directed energy apparatus, the system comprising:

a memory; an electronic controller coupled to the memory and configured to:

manage an auxiliary cooling system to maintain the directed energy apparatus below a target temperature;

detect when to initiate an absorption cycle of a thermal sorption system, wherein the thermal sorption system is in thermal communication with the directed energy apparatus; and

initiate the absorption cycle, in response to detecting when to activate the absorption cycle, wherein the absorption cycle comprises a plurality of refrigerant pulses, with each pulse within the absorption cycle including a pulse of refrigerant followed by a rest 5 period.

**14.** The system of claim **13**, wherein to detect when to initiate the absorption cycle, the electronic controller is configured to determine a thermal load.

**15.** The system of claim **13**, wherein to detect when to initiate the absorption cycle, the electronic controller is configured to determine an activation of the directed energy apparatus. 10

**16.** The system of claim **13**, wherein to initiate the absorption cycle, the electronic controller is configured to initiate the absorption cycle in advance of activation of the directed energy apparatus. 15

**17.** The system of claim **13**, wherein the plurality of refrigerant pulses comprises two or more refrigerant pulses per absorption cycle. 20

**18.** The system of claim **13**, wherein the directed energy apparatus is a directed energy weapons system that heats in relatively short bursts as the directed energy weapons system is discharged.

**19.** The system of claim **13**, wherein the directed energy apparatus comprises a directed energy weapons system comprising a laser weapon system, electro-laser weapon system, or microwave weapon system. 25

**20.** The system of claim **13**, wherein the auxiliary cooling system comprises a vapor compression cooling system. 30

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